भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

BELLE

$b \to s\ell\ell$ decays at Belle

[1]S. Choudhury, [2]S. Sandilya, [3]K. Trabelsi, [1]A. Giri

[1]IIT Hyderabad, [2]Uni. of Cincinnati, [3]LAL/KEK

December 14, 2018

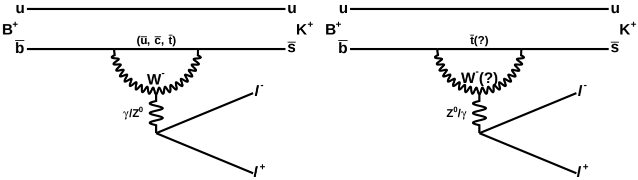
XXIII DAE-BRNS HIGH ENERGY PHYSICS
SYMPOSIUM 2018
December 10 - 14, 2018

Outline

1. Introduction
2. Test of Lepton Flavor Universality (LFU) and status of R_K, R_K^*
3. R_K sensitivity at Belle
4. Search for Lepton Flavor Violating (LFV) decays $B^+ \to K^+ \ell\ell'$
5. Search for LFV decays $B^0 \to {K^*}^0 \ell\ell'$ [PRD 98.071101(R) (2018)]
6. Conclusion

Introduction

- $b \to s$ quark transition are FCNCs. These processes occur through penguin loop and box diagrams in SM.



- These decays are highly suppressed and very small BR ($\mathcal{O}$ (10^{-6})).
- These decays are very sensitive to NP.
- Probes NP models at energy scales higher than direct searches ($\sim$100 TeV).

New physics can contribute by:

- enhancing or suppressing decay rates.
- modifying the angular distribution of the final state particles.

Introduction

- The amplitude of a hadron decay process is described as:

$$A(M \to F) = \langle F|\mathcal{H}_{eff}|M\rangle = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\mu) \langle F|O_i(\mu)|M\rangle$$

CKM couplings — Wilson Coefficients (μ = scale) — Hadronic Matrix Elements

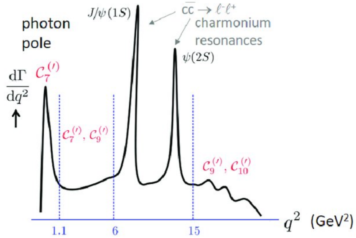
Wilson coefficients C_i = Perturbative short distance effects

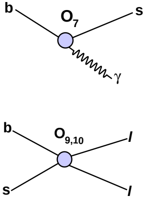
Operators O_i = non-perturbative long distance effects.

$i = 7$: Photon penguin

$i = 9, 10$: Electoweak penguin

- NP can affect SM operator contributions (Wilson coefficients) and/or enter through new operators.



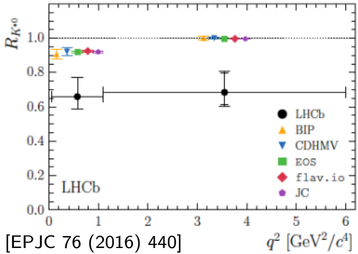


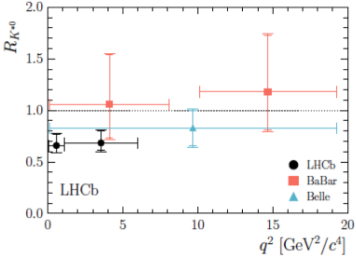
- Contribution of C_7, C_9 and C_{10} depends on q^2 (invariant mass square of two leptons).

Test of Lepton Flavor Universality (LFU) (R_K^*)

LFU in $B^0 \to K^{*^0} \ell^+ \ell^-$

- LHCb measurement of
  $R_{K^*} = \dfrac{BR(B^0 \to K^{*^0} \mu^+ \mu^-)}{BR(B^0 \to K^{*^0} e^+ e^-)}$ shows deviations from SM expectation.
  $R_{K^*}(0.045 < q^2 < 1.1 \text{ GeV}^2/c^4) = 0.66^{+0.11}_{-0.07} \pm 0.03$
  $R_{K^*}(1.1 < q^2 < 6 \text{ GeV}^2/c^4) = 0.69^{+0.11}_{-0.07} \pm 0.05$
- Compatibility with the SM estimated to be at the level of $2.1 - 2.3\sigma$ for low q^2 and $2.4 - 2.5\sigma$ at central q^2 for a data sample of 3fb^{-1}.
- Belle measurement for whole q^2 region, $R_{K^*} = 0.83 \pm 0.17 \pm 0.08$, is consistent with SM prediction.





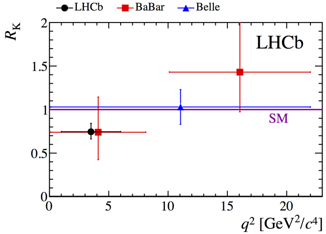
- ▲ BIP [EPJC 76 (2016) 440]
- ▼ CDHMV [JHEP 04 (2017) 016]
- ■ EOS [PRD 95 (2017) 035029]
- ◆ flav. io [EPJC 77 (2017) 377]
- ● JC [PRD 93 (2016) 014028]

- ● LHCb [JHEP 08(2017) 055]
- ■ BaBar [PRD 86 (2012) 032012]
- ▲ Belle [PRL 103 (2009) 171801]

Test of LFU (R_K)

LFU in $B^+ \to K^+\ell^+\ell^-$

- Theoretically, similar to $B \to K^*\mu^+\mu^-$, but K is a scalar.
- These observables are theoretically very clean, as most of the hadronic uncertainties cancel out in the ratio.
- LHCb (PRL 113, 151601(2014)) shows deviation from SM
  $R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$
  in $q^2 = [1-6]$ GeV$^2/c^4$: 2.6σ tension for $3\mathrm{fb}^{-1}$ data sample.
- The value of R_K for Belle was consistent with unity within the uncertainty limit measured for a data sample of $605\mathrm{fb}^{-1}$.
- Currently, the study of R_K with Belle full data sample ($711\mathrm{fb}^{-1}$) is going on, I will present here the sensitivity.



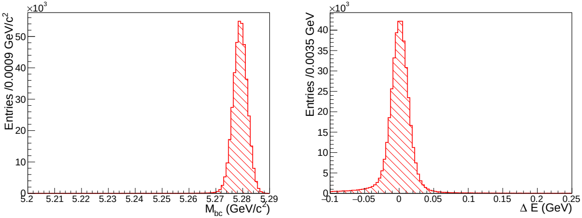
- ● LHCb [PRL 113(2014) 151601]
- ■ BaBar [PRD 86 (2012) 032012]
- ▲ Belle [PRL 103 (2009) 171801]

R_K sensitivity at Belle

- The decay channels used are $B^+ \to K^+\ell\ell$ and $B^0 \to K_S^0\ell\ell$, where, $\ell\ell = \mu\mu$ or ee.
- $K^\pm$, $\mu^\pm$ and $e^\pm$ particles satisfying PID are selected from tracks near IP. K_S^0 are selected using K_S^0 displaced vertex properties and with a mass window of $0.487 < M_{K_S^0} < 0.508$ GeV$/c^2$.
- The kinematic variables those differentiate signal from background are

$$M_{bc} = \sqrt{E_{beam}^2 - |p_B|^2}$$
$$\triangle E = E_B - E_{beam}$$

where, E_{beam} refers to the beam energy, which is half the center of mass (CM) frame energy. E_B and p_B are energy and momentum of B candidate.



R_K sensitivity at Belle

- **Peaking Backgrounds:** The peaking backgrounds from $B \to KJ/\psi(\ell\ell)$ and $B \to K\psi'(\ell\ell)$ are vetoed by applying q^2 cut;

$$8.5 < q^2 < 10.2 \text{ GeV}^2/c^4 \text{ for } J/\psi$$
$$13 < q^2 < 14 \text{ GeV}^2/c^4 \text{ for } \psi(2S)$$

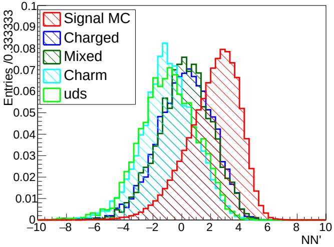
  The other peaking from $B \to D^0(K\pi)\pi$ (pion assumed muon mass hypothesis) is removed by applying invariant mass cut *i.e.*, $1.85 < M_{K\pi} < 1.865 \text{ GeV/c}^2$.

- A Neural Network (NN) is trained with some event shape (LR KSFW, $\cos_{\theta_B}$, $\cos_{\theta_T}$,...), vertex quality (ΔZ, $\chi^2(K\ell\ell)$,...) and kinematic ($E_{vis}^{(ROE)}$, E_{miss}...) variables to suppress background from continuum and generic B-decays.

- The NN output is translated to NN' using

$$\text{NN}' = \log \frac{\text{NN} - \text{NN}_{\text{min}}}{\text{NN}_{\text{max}} - \text{NN}}$$

  where, $\text{NN}_{\text{min}} = -0.6$ is the minimum NN cut applied. NN_{mix} is the maximum NN value and is obtained from signal MC.



- The minimum cut reduces $\sim 75\%$ of backgrounds, with $\sim 95\%$ signal efficiency retention.

- NN' has similar distribution for different q^2 bins for signal as well as backgrounds $\to$ same PDF can be used for different q^2 regions.

R_K sensitivity at Belle

- 3D fit is performed using M_{bc}, ΔE and NN'.
- PDF are modeled as:

	Signal	generic B	Continuum
ΔE	Crystal Ball + Gaussian	Exponential	Chebychev polynomial
M_{bc}	Gaussian	Argus	Argus
NN'	Bifurcated Gaussian + Gaussian	Gaussian	Gaussian

- $R_K(J/\psi) = 1.00 \pm 0.01$ (data), value is found to consistent with unity within the uncertainty in MC as well as in data.
- $B \to KJ/\psi(\ell\ell)$ is used to calibrate signal PDF of $B \to K\ell\ell$.
- Off-resonance sample which is taken 60 MeV below $\Upsilon(4S)$ resonance, used to study continuum background and fix the PDFs shapes.
- The backgrounds PDFs parameters for generic B decay are floated.

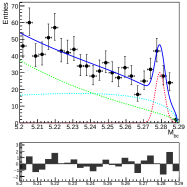


Figure: M_{bc}

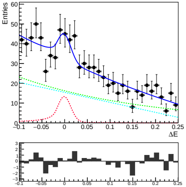


Figure: ΔE

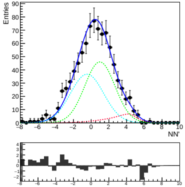


Figure: NN'

R_K sensitivity at Belle

- 3D fit is performed using M_{bc}, ΔE and NN'.
- PDF are modeled as:

	Signal	generic B	Continuum
ΔE	Crystal Ball + Gaussian	Exponential	Chebychev polynomial
M_{bc}	Gaussian	Argus	Argus
NN'	Bifurcated Gaussian + Gaussian	Gaussian	Gaussian

- $R_K(J/\psi) = 1.00 \pm 0.01$ (data), value is found to consistent with unity within the uncertainty in MC as well as in data.
- $B \to KJ/\psi(\ell\ell)$ is used to calibrate signal PDF of $B \to K\ell\ell$.
- Off-resonance sample which is taken 60 MeV below $\Upsilon(4S)$ resonance, used to study continuum background and fix the PDFs shapes.
- The backgrounds PDFs parameters for generic B decay are floated.

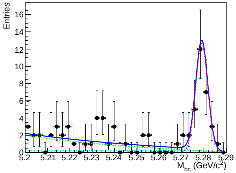


Figure: M_{bc} projection

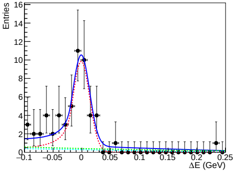


Figure: ΔE projection

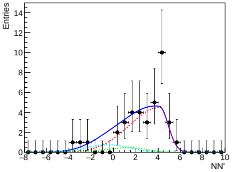
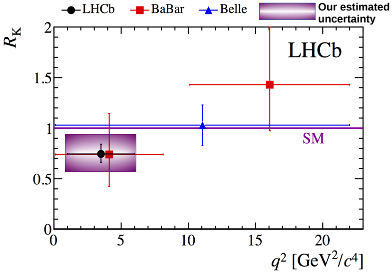


Figure: NN' projection

- Signal region: $M_{bc} > 5.27$ GeV$/c^2$, $-0.05 < \Delta E < 0.05$ GeV and NN'> 0.5.

R_K sensitivity at Belle

- The R_K uncertainty of Belle for whole q^2 region was 0.19 (statistical), measured for a data sample of $605\mathrm{fb}^{-1}$ [PRL 103,171801(2009)].
- Our current expected statistical uncertainty is $\mathbf{0.2}$ for a bin of $1 < q^2 < 6$ GeV$^2/c^4$ and $\mathbf{0.1}$ for whole q^2 region.
- If we consider LHCb result as central value, then the violet box shows our estimated uncertainty.



- The R_K estimation for high q^2 region is in progress.

Search for Lepton Flavor Violating (LFV) decays $B^+ \to K^+\ell\ell'$

- The deviation from SM expectation in R_K and R_{K^*} from LHCb result possibly show LFU violation.
- LFV can come together with LFU violation (S. L. Glashow et.al PRL 114, 091801 (2015)).
- Currently Belle has published LFV decays $B^0 \to K^{*^0}\ell\ell'$, where $\ell = \mu, e$ [PRD 98.071101(2018)].
- We are also studying LFV decays $B^+ \to K^+\ell\ell'$, where $\ell = \mu, e$.

- Applied same particle selection criteria as that of R_K study.
- The main sources of peaking backgrounds are removed by applying invariant mass cut on events, coming from $B \to KJ/\psi(\ell\ell)$ *i.e.*, $3.06 < M_{\ell_1\ell_2}, M_{K\ell_2} < 3.12\ \mathrm{GeV/c^2}$ and around D^0 mass region for $B \to D^0(\to K\pi)\pi$, *i.e.*, $1.84 < M_{K\ell_2} < 1.86\ \mathrm{GeV/c^2}$.
- 3D fit is performed using M_{bc}, ΔE and NN'.
- $B \to KJ/\psi(\ell\ell)$ ($\ell\ell = \mu\mu$ and ee) behave as control sample for these LFV modes.
- Fitting procedure is almost similar to R_K study, but here we have merge background in a single component.

Search for LFV decays $B^+ \to K^+ \ell \ell'$

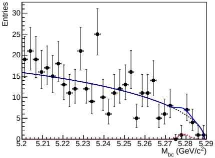


Figure: M_{bc} Projection

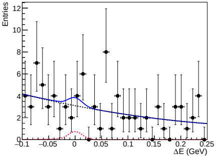


Figure: ΔE Projection

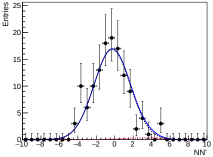


Figure: NN' Projection

- The expected upper limit on BR with 90% CL is estimated by

$$\mathcal{B}^{(\mathcal{UL})} = \frac{N_{sig}^{(UL)}}{N_{B\bar{B}} \times \varepsilon}$$

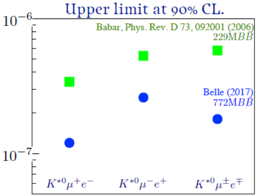
where, $N_{sig}^{(UL)}$ is number of signal events in the upper limit,
ε is signal yield efficiency,
$N_{B\bar{B}}$ is number of $B\bar{B}$ pairs $= 7.7 \times 10^8$.

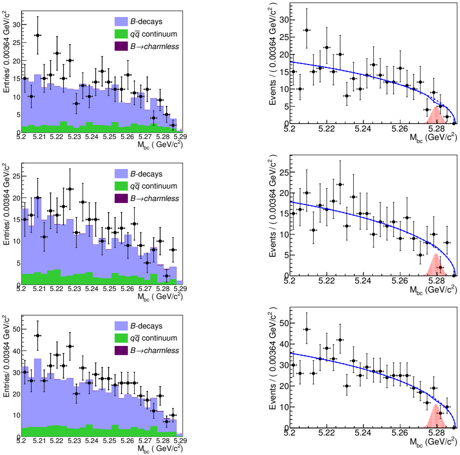
Mode	ε (%)	$N_{sig}^{(UL)}$	$\mathcal{B}^{(\mathcal{UL})}$ ($\mathbf{10^{-8}}$)	PDG $\mathcal{B}$ (10^{-7})
$B^+ \to K^+ \mu^+ e^-$	29.3	4.4	**2.0**	< 1.3
$B^+ \to K^+ \mu^- e^+$	30.0	4.9	**2.1**	< 0.9

- Our estimated upper limit are an order of magnitude better than that of the PDG upper limits, which are from BaBar [PRD 73(2006)092001].

Search for LFV decays $B^0 \to K^{*^0} \ell \ell'$

- The modes studied are $B^0 \to K^{*^0} \mu^+ e^-$ and $B^0 \to K^{*^0} \mu^- e^+$ [PRD 98.071101(R)(2018)].
- Strong contribution from continuum and generic B backgrounds.
- Trained two NN to suppress backgrounds.
- Good agreement between data and MC.
- No evidence of signal observed $\to$ upper limit is estimated.





Mode	ε (%)	N_{sig}	$N_{sig}^{(UL)}$	$\mathcal{B}^{(\mathcal{UL})}$ (10^{-7})
$B^0 \to K^{*^0} \mu^+ e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	5.2	1.2
$B^0 \to K^{*^0} \mu^- e^+$	9.3	$0.4^{+4.8}_{-4.5}$	7.4	1.6
$B^0 \to K^{*^0} \mu^\pm e^\mp$	9.0	$-1.2^{+6.8}_{-6.2}$	8.0	1.8

Conclusion

- Several anomalies in B decays indicating lepton non-universal interactions.
- LFU tests are extremely clean probes for NP.
- Particular interest is in ratio testing LFU since they are not affected by hadronic uncertainties.
- Anomalies indicating LFU, in general we should also observe LFV processes.
- Belle searched LFV $B^0 \to K^{*^0}\mu^{\pm}e^{\mp}$ and the most stringent limit is found.
- Belle will publish soon the result of R_K and R_{K^*} with full data sample, including LFV decay modes ($B^{\pm} \to K^{\pm}\mu^{\pm}e^{\mp}$).

Observables	Belle 605/711fb^{-1}	BelleII 5ab^{-1}	BelleII 50ab^{-1}
R_K ([1.0, 6.0] GeV^2)	–	11%	3.6%
R_K (> 14.4 GeV^2)	–	12%	3.6%
R_{K^*} ([1.0 – 6.0] GeV^2)	–	10%	3.2%
R_{K^*} (> 14.4 GeV^2)	–	9.2%	2.8%
R_K (whole q^2)	19%	–	–
R_K ([1.0, 6.0] GeV^2)	22%	–	–